ELECTRICAL BREAKDOWN PHENOMENA INVOLVING MATERIAL INTERFACES

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Abstract

Electrical breakdown in a composite gas-solid dielectric is described in qualitative terms. Continuum- and particle-based calculations are performed on idealized structures. The analysis and the calculations suggest that dielectric permittivity has an important role at early times in the breakdown events. The continuum calculations show that the space-charge limited current in the solid dielectric has an important role at longer times. At very long times, the Joule heating from the space-charge limited current is expected to produce thermal breakdown.

I. INTRODUCTION

Classical electrical breakdown in its most simple form involves two electrodes separated by a dielectric that may be a gas, a liquid or a solid [1], [2]. The phenomena become more complex if another material interface is involved. In this case, the basic structure consists of an electrode, gas, solid dielectric and another electrode. In this work, we focus on electrical breakdown in a composite dielectric consisting of a gas and a solid.

Such composite dielectrics occur in important applications. A composite structure, with one electrode covered by an insulating dielectric, is used as a device to create ozone through chemical reactions involving reactive species created by the electrical discharge [3]. The glow discharge breakdown in such devices is called dielectric barrier discharge (DBD) [3]. In this application, the dielectric barrier limits the breakdown to glow discharge [4], [5]. This limitation occurs because the electrical discharge deposits charge into the solid dielectric; the resultant electric field quenches the discharge [4], [5].

Another important application is as lightning arresters [6], [7]. In this case, the solid dielectric helps to initiate electrical breakdown between the electrodes by reducing the time for the discharge growth [7]. This time duration must be short to make the device effective as a protective device [6], [7]. A related structure, called a lightning arrester connector (LAC), has a similar function but it is more complicated because it is in the form of a coaxial cable connector [8], [9]. Finally, research on the formative-time of breakdown has revealed that it is reduced and controlled by the presence of dielectric

particles on the surface of the cathode electrodes [10]. In this case, the solid dielectric serves as sources of electrical discharge [10].
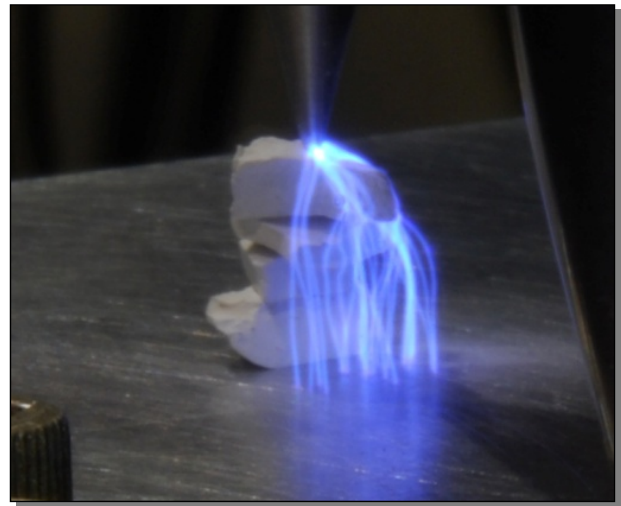

Figure 1. Photograph showing air breakdown involving a single rutile particle between point-plane electrodes. In some cases, the luminous discharge filaments hug the rutile surface.

The motivation for the calculations to be described is a series of experiments on individual rutile (TiO_2) particles [11]. In these experiments, each particle is placed between electrodes and subjected to a transient electrical potential. As shown in the photograph in Figure 1, a luminous discharge current flows between a point electrode and a bottom planar electrode. The air discharge filaments strike the particle and flow around it. In some cases, the filaments appear to flow through pores or cracks in the particles. In many cases, they appear to "hug" the surface as shown in the photograph.

The surface discharge can lead to permanent increases in the conductivity. In earlier work, surface tracks have been correlated with the regions of increased conductivity [12], [13].

The cause of the surface tracks is hypothesized to be thermal breakdown of the rutile particle in a region near the surface. This hypothesis is consistent with previous research [12], [13]. As part of this hypothesis, it is assumed that this dielectric breakdown originates as air breakdown and that some of the electrons released in the air breakdown are collected in the rutile particle. Then

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14. ABSTRACT
Electrical breakdown in a composite gas-solid dielectric is described in qualitative terms. Continuum- and particlebased calculations are performed on idealized structures. The analysis and the calculations suggest that dielectric permittivity has an important role at early times in the breakdown events. The continuum calculations show that the space-charge limited current in the solid dielectric has an important role at longer times. At very long times, the Joule heating from the space-charge limited current is expected to produce thermal breakdown.

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rutile undergoes thermal breakdown driven by the Joule heating of the injected electrons.
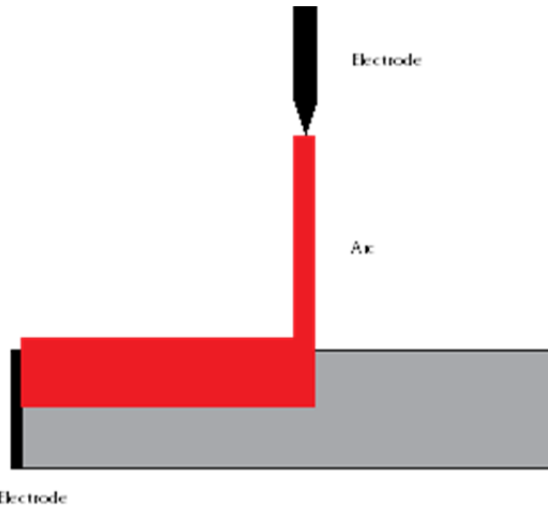

Figure 2. Schematic showing electrical breakdown involving a gas and a solid dielectric. At short times, the high permittivity of the dielectric makes the insulator conductive. The consequent gas breakdown produces a conductive filament. At later times, the space-charge limited current flows in the solid dielectric. At very long times, the Joule heating causes thermal breakdown along the surface.

The goal of this paper is to explore the breakdown in composite dielectrics. A further goal is to contribute information to examine thermal breakdown. An important factor is the permittivity of the rutile. As will be discussed, the electrical current at later times is space-charge limited

II. QUALITATIVE DISCUSSION

The goal of these particular calculations is to understand breakdown in simple composite dielectrics. In this qualitative discussion, only one particle is considered as in Figure 1.

The breakdown calculations to be described are focused on the idealized structure shown in Figure 2. This figure illustrates electrical breakdown in a composite gas-solid dielectric. It shows breakdown in the gas and along the surface of the solid. It is expected that the gas breakdown occurs first. An important contribution is the fact that the dielectric acts as a metal at short times. Thus it hosts a large displacement current that can be long enough to cause gas breakdown. After a conductive channel is established in the gas, the electrical potential in the solid dielectric begins to rise. Also, electrons from the gas discharge are collected in the solid insulator. This electrical current begins to heat the solid as it grows and as the electric field increases. The electric field caused by

the injected electrons opposes the applied bias. Thus this current becomes space-charge limited. If the applied voltage is sufficiently large, the current remains large enough to support the current in the gas discharge. Eventually, the Joule heating leads to thermal breakdown in the solid.

Initially the gas breakdown contributes all the electrons. These electrons are energetic relative to the electrons in the solid. Thus they tend to create electron-hole pairs that increase the conductivity of the solid. The most energetic injected electrons cause the release of some electrons through secondary electron emission (SEE). Eventually, a balance is reached between the collected electrons and SEE.

It is postulated that a critical applied voltage is needed to produce thermal breakdown. Above this critical voltage, the electric field continues to support gas breakdown leading to thermal breakdown at long times. Also the amount of heat released may cause permanent changes in the solid in the form of surface tracks. The final surface breakdown will involve both gas breakdown near the gas-solid interface and also thermal breakdown of the solid. Below this critical voltage, the gas breakdown ceases as the opposing electric field from the deposited charge rises. This quenching of breakdown at long times is consistent with the work on DBD [4], [5].

III. THEORY

Both a particle method and a continuum method are used for the calculations. A ensemble Monte Carlo (EMC) method, based on particles, is used for the fundamental calculations to examine the effects of the gas-solid interface. A continuum method, REOS, is used for the full transient current calculations.

A. The Particle Method: Ensemble Monte Carlo (EMC)

In these calculations the Boltzmann transport equation is solved for an ensemble of electrons and holes in momentum space. These particles are driven by the electric field and undergo scattering by phonons. The most energetic electrons undergo plasmon emission. They also undergo impact ionization and Auger recombination. Finally, they can surmount the barrier at the interface between the solid and the gas. The rate of this secondary electron emission (SEE) is the primary focus of these EMC calculations.

B. The Continuum Method: REOS

The continuum calculations to be described focus on space-charge limited breakdown in the solid dielectric [14]. These calculations use drift-diffusion expressions for the currents in particle continuity equations. The effects of Joule heating are taken into consideration.

For this paper, the calculations are made simple but the effects of differing materials and their interfaces are included. For the calculation to be discussed, the only

species included are electrons and holes (ions) in all the regions. The kinetic equations for the electron n and ion (hole) p densities are:

$$\frac{dn}{dt} = \frac{1}{q} J_n + \alpha_n \mid J_n \mid + S_n$$

$$\frac{dp}{dt} = -\frac{1}{q} J_p + \alpha_n \mid J_p \mid + S_p$$

In these continuity equations, the second term represents Townsend avalanching [1], [15]. The last term represents sources and sinks of electrons and holes. The currents are drift-diffusion currents for both species. In a similar way, an equation for the Joule heating is written for the temperature of the gas and the solid.

The Poisson equation,

$$\nabla^2 \phi = \frac{\rho}{\varepsilon \varepsilon_0}$$

is solved to obtain the electric field $E = -\nabla \phi$ in terms of the charge density:

$$\rho = p - n.$$

IV. RESULTS AND DISCUSSION

In this section, the EMC and REOS calculations are discussed.

A. EMC Results

The EMC calculations focus on the loss of energy of energetic electrons that strike the rutile surface. The goal of these calculations is to produce information for the REOS calculations.

These one-dimensional calculations focus on the collection of electrons from the gas by the solid. In these calculations, energetic electrons enter the solid at a preset rate. The Monte Carlo method is used to compute the most likely consequences.

Figure 3 shows the effects of 3 eV electrons that strike the solid at a rate of 10^{14} s^{-1}. As seen in the figure, the population of injected electrons rises with a nearly constant rate. As can be seen at short times, each energetic electron creates approximately two electron-hole pairs. In these calculations, the electron-hole pairs are created by impact ionization. For these calculations, the incident electron energies are below the threshold for plasmon emission. Thus this process, which also leads to impact ionization, does not contribute for these incident electrons. All the electrons and holes tend to cool by phonon emission as they diffuse away from the interface and are collected at the back of the solid. A small fraction of the electrons maintains enough energy to be emitted from the solid. This process is called secondary electron emission (SEE).

For more energetic incident electrons, plasmon emission leads to energetic electrons that also cause impact ionization.

A comparison of the physics in these calculations with the physics in the present REOS calculations revealed a loss of information in the continuum calculations. This information loss is a consequence of using a single temperature to characterize the electron population. The end result is that hot incident electrons are assigned a common temperature without an opportunity to undergo impact ionization. An important goal of these EMC calculations is to produce insight about how to overcome this problem.

B. REOS Results

The REOS calculations focus on the temporal evolution of the electrical current in the solid dielectric. These currents are the displacement and space-charge limited currents. These currents are necessary to explore the Joule heating in the solid.

A series of one-dimensional calculations on metal-gas-solid-metal structures were performed to obtain insight about electrical breakdown in the solid. These calculations reveal that the gas discharge is quenched if the electrical bias is low. These conclusions are consistent with earlier work [10], [11].
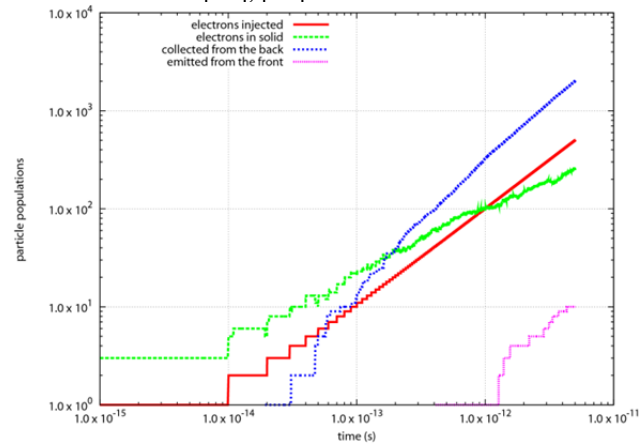

Figure 3. EMC results that showing the collection of air discharge electrons in the rutile. The energetic electrons create approximately two electron-hole pairs in the rutile by impact ionization. A very small fraction of these electrons is emitted.

As will be discussed, these calculations illustrate the role of the displacement current in the solid insulator at short times. As a consequence, the applied potential tends to cause gas discharge. The role of the large permittivity of rutile (approximately 86) is to extend the duration of this current flow. An important consequence is an increased likelihood of air discharge.

A series of calculation are described to focus on the flow of electrical current in the solid dielectric. Figure 4 shows a plot of the electron density in the composite structure. This structure is similar to the structure shown

in Figure 2. In this structure, the material regions along the x-direction are the electrode (cathode), air gap and the rutile. The anode electrode is located in one corner of the rutile. The electron density is highest in these electrode regions. The solid and gas regions have much lower electron density.

Figure 4 shows the electron density early in the growth of the air discharge in the form of a conductive filament consisting of electrons and ions. This filament is created by temporal pulse that creates a distribution of electrons and ions in a narrow channel. This discharge is the region of increased electron density in the gas region of the figures.
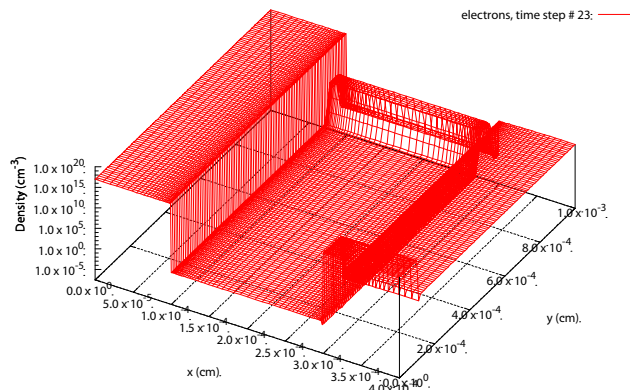

Figure 4. Shows the electron density early in time.

At this time, the current in the rutile is nearly entirely displacement current. However, the electrical potential is nearly unchanged because the permittivity is very large.

As time progresses, some electrons from the air discharge channel enter the solid. These electrons flow normal to the interface at first. Then they begin to flow along the interface to the other electrode, the anode. This flow becomes limited by the electrical potential caused by the injected electrons. Thus it is a space-charge limited current.
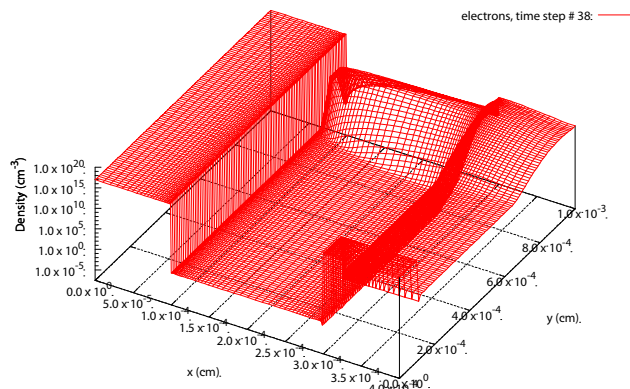

Figure 5. Shows the electron density at a later time. In this case, the space-charge limited current in the rutile region is very prominent.

Figure 5 shows the electron density later in time. The electron density in the solid now exceeds the density in the gas filament. At much longer times, not shown, the electron density becomes nearly uniform. In this case, the applied potential is large enough that it can drive the electron current.

V. FURTHER DISCUSSION

The results from a more complete set of calculations are expected to produce effects similar to those seen in DBD if the applied potential is reduced. The present calculations suggest that if the applied potential is lower than a critical potential, then the discharge will be quenched, in agreement with earlier work [4], [5]. However, if the potential exceeds a critical potential, the the space-charge limited current will prevail. The end result is expected to be thermal breakdown in a filament that penetrates the solid dielectric.

Further calculations will include additional effects of the collected electrons. One effect is the increased charge density caused by impact ionization. This phenomenon is illustrated in Figure 3. Another effect is the direct heating by these collected electrons.

VI.   SUMMARY

The calculations discussed in this paper focus on two aspects of electrical breakdown of a composite gas-solid dielectric. One, the collection of electrons in the solid caused by the gas filament striking the solid. Two, the space-charge limited breakdown of the solid. Both effects are consistent with a surface discharge that hugs the rutile surface. First, electrons tend to be collected by the rutile. Second, those electrons cause Joule heating of the rutile. At long times, this Joule heating may cause thermal breakdown that may lead to conductive tracks.

VII.   ACKNOWLEDGMENT

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